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# On the nature of charged particle flow of vacuum arc

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**Abstract.** Time resolving investigations of charged particles flow from the cathode region of the vacuum arc reveal that the basis of charged particles flow is short-term burst. These bursts can form sequences, groups with a relatively smooth waveform and superbursts. The Fourier analysis showed that ion flow has a brown-like frequency law. This fact can serve as evidence of the fractal nature of the cathode spot. However, the detailed analysis of ions and accelerated electron signals revealed that the fractal nature of charged particle signal can reflect the fractal nature of plasma turbulences in discharge plasma. Also, the strong correlation between intensive charged particle flow appearance and arc discharge parameter instabilities was revealed. Thus, the plasma instabilities can be considered as the cause of ion and electron flow acceleration in the vacuum arc.

## 1. Introduction

The ion flow of middle and high-current vacuum arc has got a great interest because it is widely used in scientific researches and industrial applications. The ion sources, based on a vacuum discharge, used in various surface modification processes. The average high current vacuum arc parameters are easy to measure because the high current arc is a stable discharge and produces sufficiently intensive charged particle flow. That is why the charged particle flow of middle and high-current vacuum arc is believed to be well investigated. It was supposed [1] that the definitive process, that governs the operation of the vacuum arc is a low current single cathode spot process. The “nonstationary” theory model supposes cathode spot to be an essentially nonstationary object. The high current vacuum arc is a cumulation of a high number of unstable cathode spots, gives stable charged flow parameters. The overlay of cathode spots operation serves as an averaging process for vacuum arc parameters. The stabilization of plasma flow parameters is confirmed by experimental methods which have a temporal resolution of more than 1  $\mu$ s. However the measurements of plasma flow parameters with sub microsecond time resolution show [2, 3] that ion and electron flow are essentially unstable even when high and middle-current vacuum arc is examined.

One of the sensitive issues in vacuum arc physics is the form of the ions energy distribution. The first measurements of the energy spectra [4] show that there is a clear dependence of the most probable energy on the ion charge state. Subsequent measurements provide controversial data. The measurement results of the Oks [5] made it possible to formulate the velocity rule: the most probable ion energies do not depend on ion charge state. An emission method for measuring the energy spectrum [6] was developed. The emission method showed that the ion energy distributions are almost



identical for different ion charge states. The independence of the ion energies from the charge state was explained by the hydrodynamic acceleration by the electron gas pressure gradient. The existence of a dependence of the ion energies on the charge was explained by the acceleration with the fall of electric potential in the region of the potential hump.

The cathode spot itself is not of great importance for practical use. However, the understanding of the mechanism of the cathode spot operation is a valuable fundamental task. To investigate the cathode spot operation, it is necessary to examine low current vacuum discharge with nanosecond time resolution.

One of the most important features of low current vacuum arc operation is the essential instability of all discharge parameters. It is well known that arc current and voltage drop, and arc plasma light emission have high amplitude oscillations with Brownian frequency dependence [7]. It was supposed [8] that these oscillations correspond to explosions of microvolumes of the cathode material ("ectons"). But it is hard to analyze these oscillations that seem to be a random one. There are more strong variations of the discharge parameters. These variations are known as the attempts of the discharge to extinct. The attempts to extinct causes of dramatically variations of light emission and particle flow intensity. The time resolving particle flow measurements, performed recently [2, 3, 9] showed that attempts of discharge to extinct causes a high intensity bursts of the charged particles flows. The present paper contains the data of recent experiments focused on the discharge choppings and attempts of the discharge to extinct.

## 2. Experimental methods

The experimental methods used for measurements of charged particle flow with sub microsecond and nanosecond time resolution are presented in figure 1. All the methods are devoted to obtaining information about the thin time structure of vacuum arc plasma flow. All the measurement methods were used in different experimental series. The method can be divided into several groups.

### 2.1. Short flight length ion collector

The using of short flight length ion collector method (see figure 1a). The collector was placed near the cathode surface (the cathode-anode net gap was 100  $\mu\text{m}$ , anode net-ion collector distance was 100  $\mu\text{m}$ ). The vacuum arc burned between the copper cathode and anode stainless steel net. The anode net was made of 5  $\mu\text{m}$  wire, the cell step was 15  $\mu\text{m}$ . Anode was a hole cylinder ( $d = 5 \text{ mm}$ ). The front edge of the anode was covered by a metal net. The ion collector was placed inside the anode cylinder. The distance from the ion collector surface and anode net was 100  $\mu\text{m}$ . The cathode and anode with ion collector made a coaxial setup with the outer grounded cylinder. The discharge was ignited with a copper pin placed on the cathode surface. The short distance between cathode surface and ion collector was used to minimize of broadening of ion current signal caused by wide energy distribution of ions.

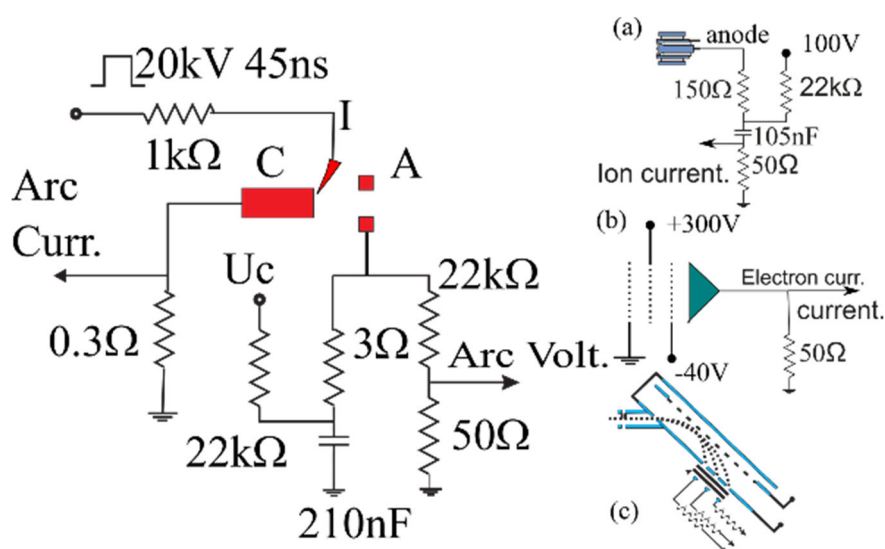
### 2.2. Electron energy analyzer

The "hot" electrons measurement was made with retarding potential electron energy analyzer (figure 1b). It had been found that there are high energy "hot" electrons in vacuum discharge plasma [3, 10]. To measure the time dependence of "hot" electron the energy analyzers with retarding potential nets were made. The frontal net was at the ground potential. Behind the frontal net the plasma breaking net was placed. The potential of plasma breaking net was +300 V. To detect hot electron the retarding net was placed after plasma breaking net. The potential of retarding net was ranged from -20 to -80 V, electrons with the energies exceeding the retarding net potential were recorded with the particle collector. The cathode material was molybdenum.

### 2.3. Multichannel ion spectrometer

The three-channel energy-mass analyzer which consists of a capacitor type electrostatic energy to charge analyzer and a time-to-flight mass to charge analyzer figure 1c. The energy analyzer consists of three plates the entrance plate, the reflecting plate and the high energy particles collector. The entrance

plate has the input slot and the three output slots. Particles with three defined energy to charge ratios are able to pass through the input and output slots. The analyzer was able to store a signal of a limited number of ion species. The limitation caused by the requirement that the duration of the ion signal must be shorter than the difference between the nearest ion species time of flight. The analyzer used in the present measurements was able to store waveforms of  $\text{Cu}^{+1} - \text{Cu}^{+3}$  and  $\text{H}^{+1}$  ion fraction. According to the method limitation the arc duration must be shorter than  $3 \mu\text{s}$ . To obtain synchronous waveforms of several ion species it was assumed that all ions accelerate near the cathode surface. This assumption made it possible to calculate all flight times of ion fractions and combine all signals in one synchronous time dependence.



**Figure 1.** Experimental methods: a) Short flight length ion collector; b) Retarding potential electron collector; c) Multichannel ion spectrometer.

All these methods allow obtaining the experimental data that confirm each other and made it possible to make new importance conclusions on the nature of the plasma flow of the vacuum arc.

### 3. Experimental results

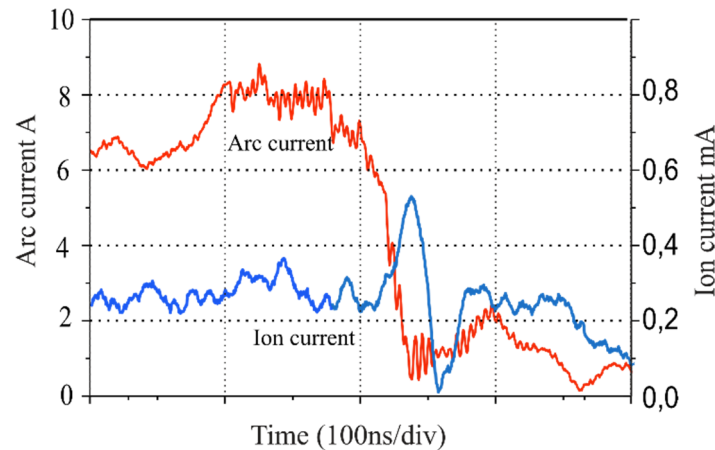
#### 3.1. The measurements of ion current with short flight length

The examination of the ion current at the nearly placed collector reveals that intensive ion current splashes at the current instabilities during the vacuum arc operation. These splashes are presented in figure 2. The correlation between the discharge current and ion collector current shows that ion current splashes correspond to local falls in the arc current. There are two possible explanations.

The correlation could be due to a time delay between plasma generation in a cathode spot and a registration of the ion current at the remote detector. The intensive splashes of ion current can be caused by synchronization of cathode spots lifecycle. Several cathode spots birth and death occur simultaneously. The synchronous appearance of several cathode spots gives a strong plasma injection in the cathode vicinity. The death of several cathodes leads to conductive plasma concentration fall that, in turn, leads to the arc current fall. The fall of the arc current coincides with delayed ion splash. But, if the majority of ions propagate with a velocity of  $2 \cdot 10^6 \text{ cm} \cdot \text{s}^{-1}$  the cathode-detector distance ( $200 \mu\text{m}$ ) would be passed in  $10 \text{ ns}$ . Thus, the ion current splash must correspond the arc current just before it's fall.

The intensive ion current splashes caused by plasma instabilities that accelerate the electrons and ions by the high amplitude electric field oscillations. The instabilities can lead to overall plasma

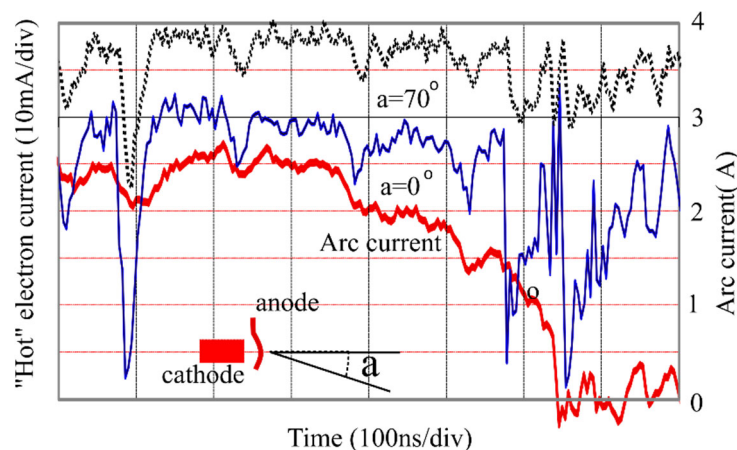
conductance fall also called abnormal plasma resistance [11]. The abnormal plasma resistance leads to falling of the vacuum arc current. But in this case the high energy electrons must occur at the moments of plasma oscillations rising.



**Figure 2.** Ion current at vacuum arc. Ion collector potential was -100 V. Final discharge chopping followed by the intensive ion current burst with duration about 30 ns.

### 3.2. Measurement of “hot electrons”

It was revealed [3, 4] that plasma of the vacuum arc has high energy (“hot”) electrons with the energies higher than interelectrode potential fall. The “hot” electrons appear at the moments of arc current instabilities (see figure 3). The “hot” electron waveforms show that the “hot” electrons appear as the intensive negative pulses at the moments of vacuum arc current local falls. The “hot” electrons pulses appear in a wide solid angle. It is important to understand that electron analyzers front apertures were at the cathode potential. Thus, the “hot” electrons appearance at the is not an effect of interelectrode potential fall influence. The average “hot” electron pulses duration was about 30–50 ns. The average duration of “hot” electron pulses is close to that of ion current splashes in experiments with method 3.1.

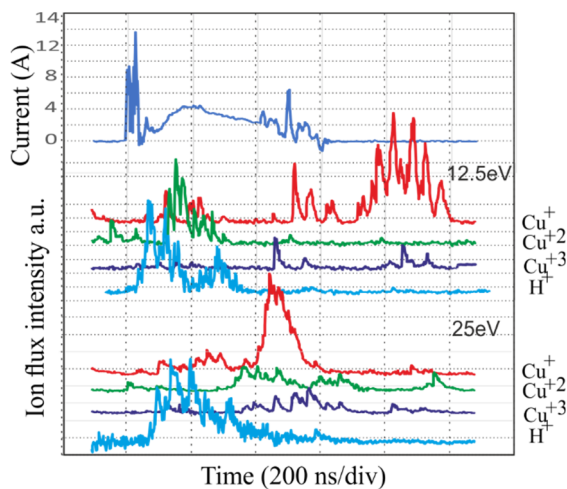


**Figure 3.** “Hot electron” current at vacuum arc current instability The “hot” electron energies were higher than 40 eV (the retarding potential was -40 V). “Hot” electrons usually appear at the instabilities of the arc current.

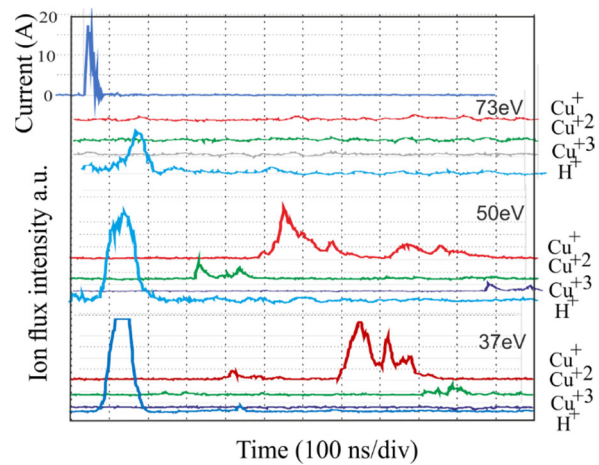
### 3.3. The measurement of mass-charge and energy composition time dependence of ion flow with a nanosecond time resolution

The signals of ion flux of the narrow energy range are essentially non-stationary even if the arc current significantly exceeds the threshold one and has no significant oscillations. It can be stated with confidence that ion flux waveforms are the set of individual pulses, which can form a relatively smooth signal (see figure 4 and 5). Ion flux waveforms show figure 4 show that there is a correlation between vacuum arc current instability and appearance of high intensive ion flux pulses. At the moments of vacuum arc choppings, the intensive pulses of singly charged ions were recorded. Some waveforms contain very intensive pulses up to 100–150 ns long (see figure 4). The amplitudes of super-pulses were several times higher than the average amplitude of pulses at the waveform. Super-emissions usually occur at the beginning of arc current instabilities. In the moments of arc chopping super-emissions consist of singly charged ions of copper or hydrogen. Besides some waveforms contain single charged ions appeared relatively long (100–600 ns) after vacuum arc chopping. The character of such superpulses or groups of pulses essentially the same as that of ion flow pulses appearing during vacuum arc operation.

To reveal the time dependence of the plasma flow of short vacuum discharge the discharge pulse with a duration of 18 ns was used. The results of the ion flow of short vacuum discharge are shown in figure 5. The ion flow consists mainly of single charged copper and hydrogen ions. The signal of hydrogen ions consists of single 100 ns superpulse appeared just after the current pulse. The signal of single charged copper ions sometimes has several pulses with 100–300 ns duration. The time delay of copper ions appearance can reach 600–700 ns. These measurements show that plasma acceleration has no strong connection with discharge operation and the presence of cathode spots generating plasma with high density.



**Figure 4.** Ion flow for several ion species for vacuum arc with strong current instabilities.



**Figure 5.** Ion flow of several ion species for very short vacuum discharge.

### 3.4. Wavelet analysis

The wavelet transformation used in the present paper was as follows:

$$\omega(a, b) = a^{-0.5} \int_{-\infty}^{+\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt, \quad (1)$$

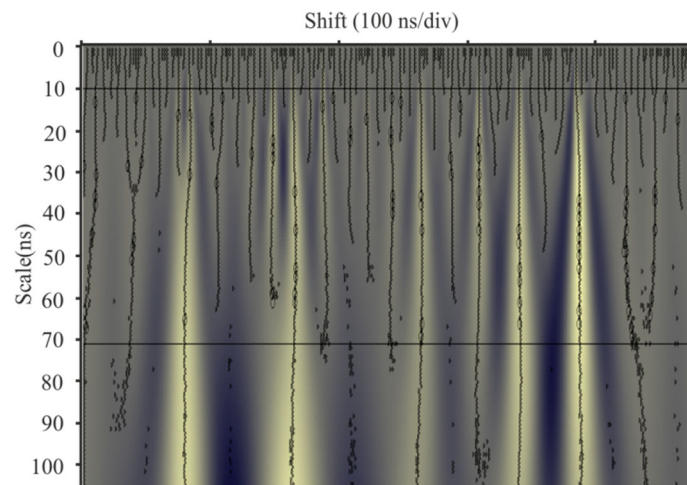
where  $a$  is scale parameter and  $b$  is the shift parameter

In all calculation the “Mexican hat” wavelet was used:



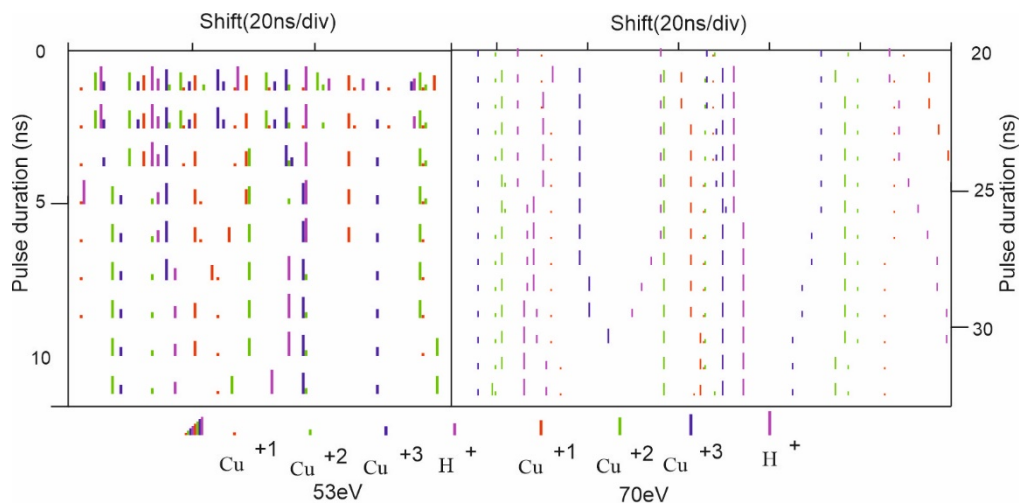
$$\psi(t) = (1 - t^2) e^{-\frac{t^2}{2}}. \quad (2)$$

The typical wavelet spectrum of  $\text{Cu}^{+2}$  with 53 eV is presented in figure 6. The black marks over the wavelet spectrum represent “skeleton diagram”. The “skeleton diagram” is formed with local maxima along the shift axis. The single waveform diagram contains not much new information. However the form of “skeleton diagram” suggests that ion flow signal has self-similarity property. The self-similarity of ion flow recently was found with Fourier analysis [7]. The form of Fourier spectra law of ion flow is close to that of the brownian process. This fact was first found by Anders[8] and was interpreted as evidence of fractal nature of the vacuum arc cathode spot.



**Figure 6.** Wavelet spectra with local maxima (wavelet skeleton diagram).

The skeleton diagram was useful to analyse the formation of energy and charge composition of ion flow. The fragments of skeleton diagram of several ion species are presented in figure 7. Two scale regions (0–10 ns and 20–30 ns) are illustrated. The diagrams show that ion fractions form complex ion flow burst in the pulse duration longer than 7 ns. At the scale region 20 ns and higher superimposed diagrams form complex ion bursts which consist of several ion fractions. Probably in the scale range 10–30 ns occur the elementary ionization processes that create final averaged mass – charge and energy composition which are well known from the literature.



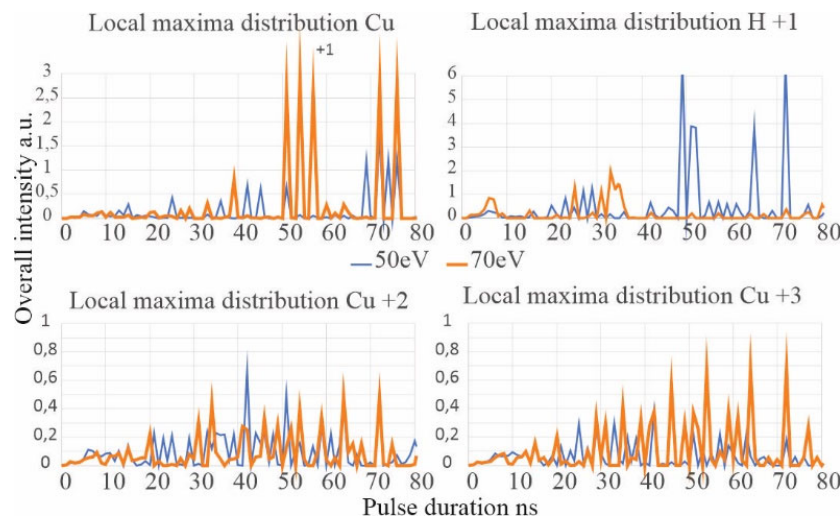
**Figure 7.** Local maxima diagram at short scale and long scale region of wavelet spectra.

To make a detailed analysis of wavelet we used local maxima method. Instead of full wavelet spectra we used only a set of local maxima  $A_{\max}^i(a, b)$ . The local maxima approach was tested by recreating the original signal from a set of maxima.

$$f(t) = \frac{1}{C_f} \int \int_{-\infty}^{+\infty} \omega(a, b) \frac{\psi\left(\frac{t-b}{a}\right)}{a^{1/2}} \geq f(t) = \sum A_{\max}^i \psi\left(\frac{t-b}{a}\right) \quad (3)$$

We have tried to find the average profile of ion burst that contains all of the ion species. The typical (averaged) ion burst profile could help to obtain a comprehensive view of the elementary process of ionization and acceleration. Obtaining the average ion burst profile turned out to be impossible because the standard deviation of the parameter the value (intensity, relative delay, pulse duration) was out of the value order of magnitude.

Local maxima approach gives pulse duration spectra of ion flux. In figure 8 the typical duration spectra of single measurement are presented. The spectra of single charge ion have intensive peaks in the ranges 20–40 ns, 50–60 ns and 70–80 ns. Double and triple charged ions have no intensive peaks in these ranges. It is possible that single charged ions play a definitive role in elementary ionization processes and multiply charged ions do not appear in every elementary ionization process.

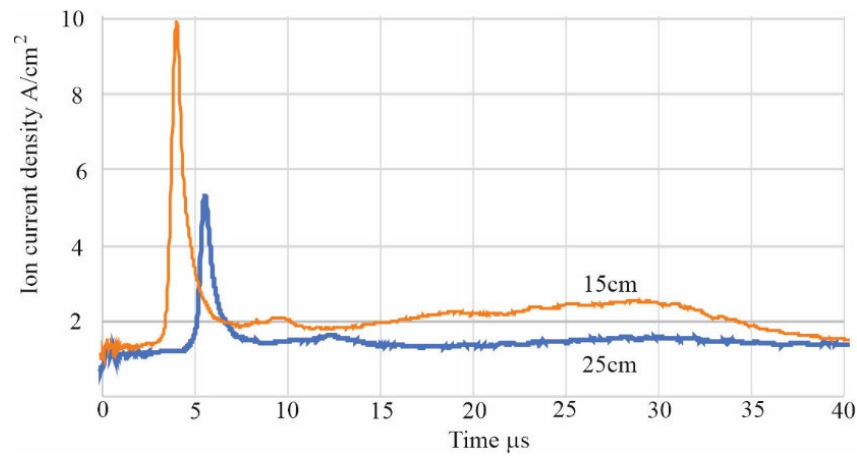
**Figure 8.** The spectra of wavelet local maxima for several ion species.

### 3.5. Ion current of kiloamp vacuum arc

We have tried to analyse the temporary character of ion flow of high current vacuum arc. In these measurements the arc current pulse of 10 kA amplitude and 12  $\mu$ s duration. Two identical ion collectors were used (figure 1a). But this time the analysers were placed at 15 cm and 25 cm from cathode surface. The ion signals last much more time than arc operation did.

The waveform of the ion signal is presented in figure 9. The measurements show that the ion current signal has several intensive peaks with a duration of about 2–10  $\mu$ s. These peaks propagate without noticeable spreading. This is the evidence of forming in the plasma flow intensive solitary waves. The velocities of the waves can be estimated as  $(5\div 8) \cdot 10^6$  cm·s<sup>-1</sup>. The form of the waves generally remains the same as they propagate. The attenuation of wave intensity is close to an inverse square law.

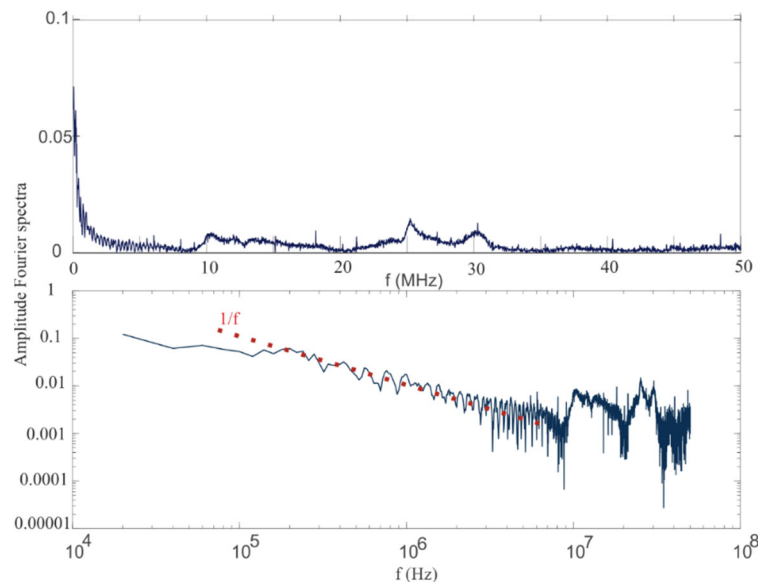




**Figure 9.** Synchronous measurement of ion current with ion detector placed at 15 cm and 25 cm distance from vacuum arc plasma source. Arc current amplitude – 10 kA.

### 3.6. Fourier analysis of ion current

The Fourier spectrum of a typical ion signal is presented in figure 10 in linear and logarithmic format. The linear view of Fourier spectrum shows that the spectrum contains local maxima that correspond to the cyclical process with a period of about 100 ns and 30 ns. These values match in common that values of local maxima in the Fourier spectrum of vacuum arc current [12] and ion flow [2]. This fact can be the evidence that the plasma of the vacuum arc for different discharges has oscillations of about 10–30 MHz.



**Figure 10.** The Fourier spectra of ion current for 10 kA vacuum arc.

The logarithmic view of Fourier spectrum gives the similar frequency dependence that was obtained for ion voltage and ion currents of low and moderate-current vacuum arcs [2, 7]. But in this case it is difficult to associate this frequency law with cathode spot operation life cycle because the main part of the signal is recorded when the discharge was no burning.

#### 4. Discussion

Experimental data on the fine time structure of vacuum arc plasma flows show that the plasma flow is essentially nonstationary for various vacuum arc conditions. In the case of low current, it is revealed that the ion flux is the sum of intense bursts with a duration from 10 to 70 ns. This nonstationarity can be explained by explosive plasma emissions from the cathode spot. In this approach, the properties of the cathode spot life cycle determine the properties of the ion flow. It was established [7] that the Fourier spectrum of the ion flow is similar to that of the Brownian process. In this case, the features of the ion flow instabilities spectrum suggest that the cathode spot has a self-similarity property, in other words, the fractal nature.

However, another explanation of the properties of plasma flows of a vacuum arc is possible. If we consider plasma as an object that can independently determine the measured parameters of the ion flux, we can get a more comprehensive explanation of most of the features of the ion flow.

The plasma usually exists in a turbulent mode. The theory of the turbulent plasma was intensively developed in the 1970s–1980s when the progress in the nuclear fusion investigations in the high temperature plasma was significant. The plasma turbulence is still the main limiting factor in achieving stable nuclear fusion reaction. One of the most important results of turbulent plasma theory [13] is the dependence of turbulence oscillations on the oscillation frequency. This dependence is called the Kolmogorov spectra

$$n_{\omega} = \frac{aP_0^{1/2}}{\omega^{\nu}} \nu = \frac{(n + \beta)}{\alpha} \quad (4)$$

where  $n_{\omega}$  is a number of turbulent waves with frequency  $\omega$ ,  $a$  is a constant,  $P$  is a power flow from lower frequencies to high frequencies,  $n$  is a dimension,  $\beta$  and  $\alpha$  are scale factors. In this model the turbulence is feeding by power flow  $P$ . The power flow is propagating toward the high frequency ranges and, finally, dissipating by the plasma viscosity.

When thermodynamic equilibrium is reached the power flow  $P_0$  falls to zero. In this case the number of waves with frequency  $\omega$  is given by

$$n_{\omega} = \frac{T}{\omega} \quad (5)$$

The number of quasiparticles with frequency  $\omega$  can relate to the amplitude of charged particles oscillations with the same frequency. Thus, the turbulence in thermodynamic equilibrium can be the cause of  $1/f$  – like the law of the vacuum arc voltage and ion current. The measured Fourier spectra dependence is close to  $1/f$  law. Thereby the turbulent plasma of vacuum arc in general is close to thermodynamic equilibrium

The abnormal plasma resistivity followed by ion flow splashes can be explained by the rising of plasma turbulence. The theory of such a process is presented in [11]. The plasma turbulence may cause acceleration of charged particles [14] accompanied by a decrease in plasma conductivity.

One of the important nonlinear effect in plasma is the existence of solitary waves – “solitons”. The existence of solitary waves is confirmed experimentally. Solitary waves can be caused by abrupt changes in plasma generation at the cathode. At the experiments in figure 9 the first wave was induced by sharp current rising. The inducing of solitary waves may be used as an explanation of results of emission method [6] that used for obtaining energy distribution with the use of flight mass spectrometer. In these experiments, the response of the plasma flow to a sharp change in the arc current was used. A sharp change of the arc current led to the propagation of a solitary wave that involved all the ion fractions. As a result, it was concluded that the energy distribution is identical for different ion fractions.

## 5. Conclusion

The new data on the temporal character of the charged particles flow suggests that the parameters of the ion flow may be formed by nonlinear effects in the plasma. Plasma turbulence makes it possible to explain the correlation of the ion current bursts and the current of hot electrons to the abnormal resistivity of the plasma. The formation of solitary waves, involving all types of ions, can lead to the absence of dependence of the most probable ion energies on the charge state.

## Acknowledgments

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